REPORT R-1592

APPLICATION
OF
FACTORIAL EXPERIMENT AND BOX TECHNIQUE
TO
BALLISTIC DEVICES

By

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and
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ORDNANCE PROJECT TS1-15
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RESEARCH AND DEVELOPMENT

GROUP

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Ordnance Project TS1-15   DA Project 502-06-001

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ABSTRACT

In an effort to reduce the time and cost of ballistic experimental development projects, the factorial experiment and Box technique have been applied to ballistic experiments with aircraft seat ejection catapults and rockets, high-low guns, Davis guns, and recoilless rifles. This has resulted in a reduction in the number of rounds fired, with little or no reduction in the validity of the analysis of variance.

A detailed discussion of application of the Box technique to the factorial data is presented. This application results in the determination of a "zone of suitable performance" which makes use of interaction effects to provide greater flexibility in the selection of design parameters.

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APPLICATION OF FACTORIAL EXPERIMENT AND "BOX" TECHNIQUE TO BALLISTIC DEVICES

INTRODUCTION

In the experimental development of ballistic systems at Frankford Arsenal we are faced with a wide variety of experimental problems. For example, in recent years we have been concerned with recoilless weapon systems, aircraft seat ejection catapults and rockets, thrusters, high-low guns, and reactionless launchers. Some of these systems are required to function repeatedly with performance variations of the order 0.1 percent; others are one-shot devices which must function reliably with performance over, under, or within certain prescribed limits. Sample size varies a great deal, as well as the type of performance requirement. In development of items such as small arms cartridges we can fire thousands of experimental rounds, while a seat ejection catapult, for example, limits us to 20 or 30 to 50 rounds.

By use of factorial experimental design techniques and analysis, combined with physical interpretation of the data in terms of response surfaces (the "Box" technique) as suggested by Dr. Box, * a tremendous flexibility of standard statistical practices has been achieved. This method has been applied in one way or another to the devices mentioned previously. As examples, our studies with the reactionless launcher, an analog computer simulation of a thruster, and the "box" of a seat ejection catapult will be discussed.

The presentation herein illustrates, in chronological order, a step by step experimental evaluation of the technique. (The experimental evaluation was preceded by an abstract evaluation which is not reported here.) First, existing data from a seat ejection catapult development was studied to determine, in a preliminary way, the method's effective- ness, the required type of experiment, and some of the experimental pitfalls. Second, a report is made of the theoretical study of a thruster, from which we learned something about the response surfaces and methods of interpolation. Finally, a discussion is presented of the reactionless launcher study. This latter study was conducted from start to finish using the experimental design methods we propose.

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*Box, G.E.P., "The Exploration and Explanation of Response Surfaces: Some General Considerations and Examples," Biometrics, Vol 10, No. 1, Mar 1954

APPLICATION OF THE "BOX" TECHNIQUE TO
M5(MOD) CATAPULT DATA

The possibility of applying the Box technique to existing data for the modified M5 seat ejection catapult was considered. Although a carefully controlled experiment, as performed in the reactionless launcher study (to be discussed later), is required to obtain fully valid results, a preliminary analysis of existing data by the Box technique was expected to give some indication of its effectiveness. Data from 24 firings of the modified M5 catapult were analyzed using three variables: temperature (T), charge (C), and web (W), each at two levels for two propellant compositions (Lots 5655.1 and 5656.1).

At that time the modified M5 catapult was to meet the following requirements:

1. The peak acceleration (g) and the rate of change of acceleration ($\dot{g}$) were not to exceed 25 g's and 300 g/second, respectively;

2. The final velocity (v) was to equal or exceed 80 fps.

The least square method was employed to fit plane surfaces* to the experimental data for g, $\dot{g}$, and v, yielding the following equations:

$$g = -308.3W + 0.13C + 0.097T + 46.1$$

$$\dot{g} = -1354W + 0.358C + 1.463T + 287.6$$

$$v = 152.1W + 0.3075C + 0.0908T + 60.08$$

where W is in inches; T, in °F; and C, in grams.

The equations were plotted for constant values of C, W, and T; i.e., the intersections of the g, $\dot{g}$, and v responses with the six planes formed by choosing constant values of C, W, and T were graphed (Figures 1 through 3). The lines on these graphs represent the intersection of the response surface with the constant planes. For example, Figure 3A depicts the intersection of the g, $\dot{g}$, and v response surfaces with the plane formed by taking the temperature as 70°F. The arrows indicate the direction of increasing magnitude of the v response surface and decreasing magnitude of the g and $\dot{g}$ surfaces.

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*The functions are not really plane surfaces. To simplify the calculations, a limited range of the parameter is chosen so that the variables can be considered a linear function of the parameters within that range. Caution must therefore be exercised when interpolating or extrapolating. For example, the origin (W=T=C=O) is not a valid point on these planes.

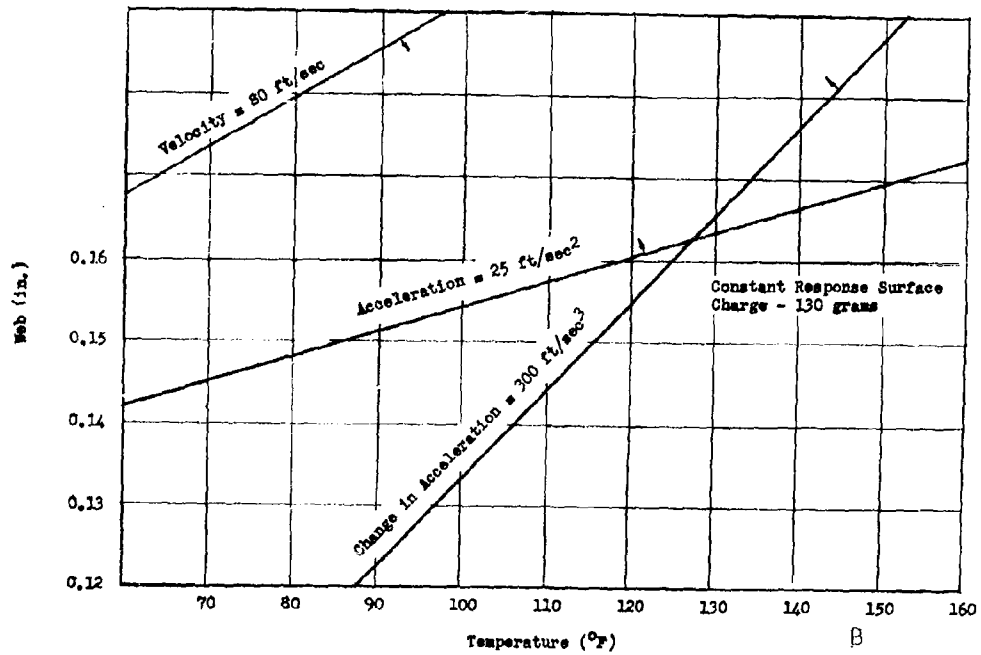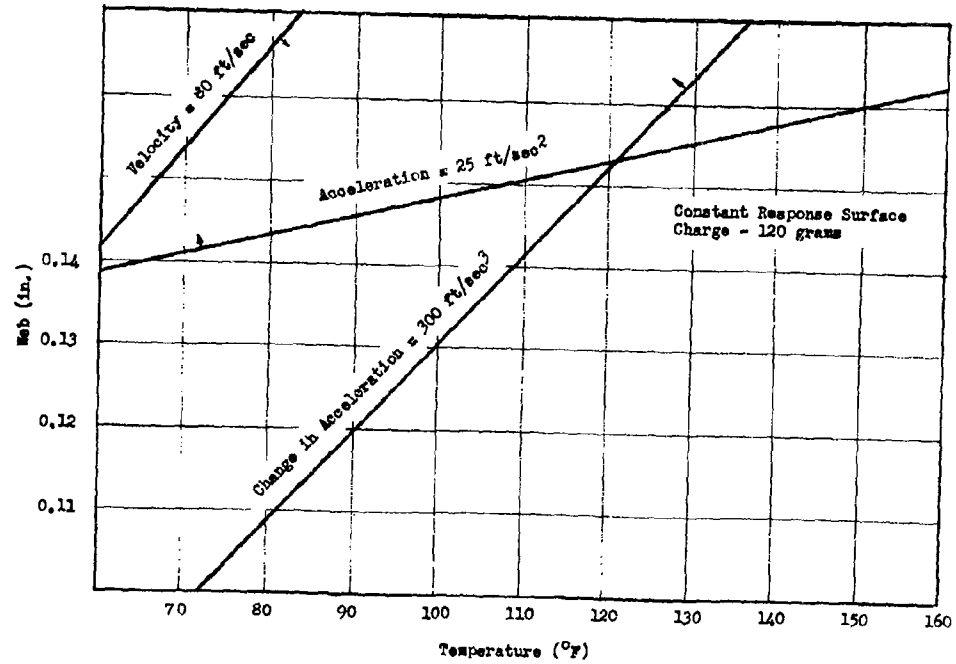Figure 1.   Constant Response Surface
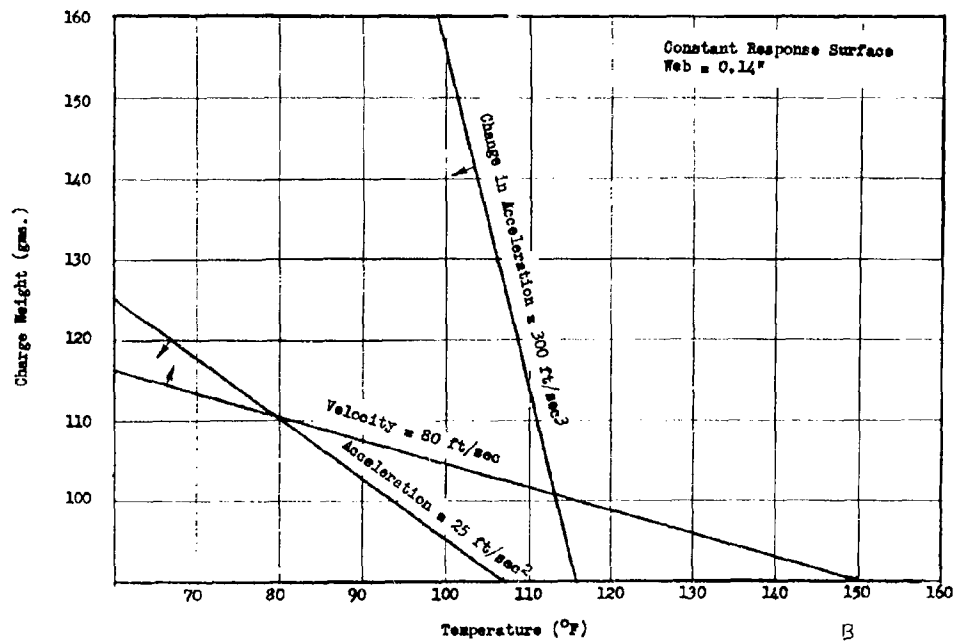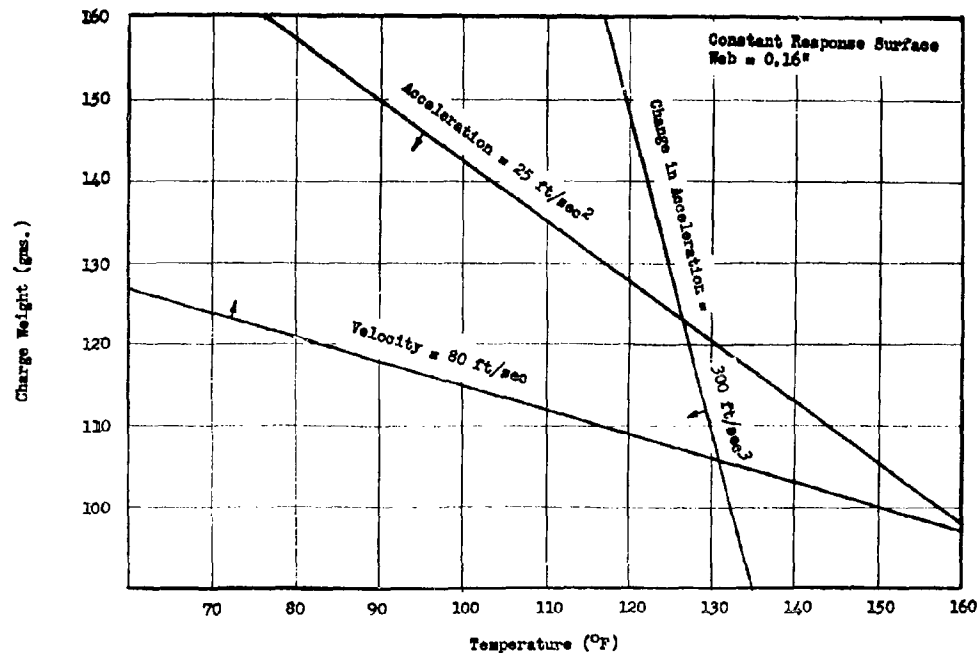A – Charge = 120 gm
B – Charge = 130 gm

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Figure 2. Constant Response Surface
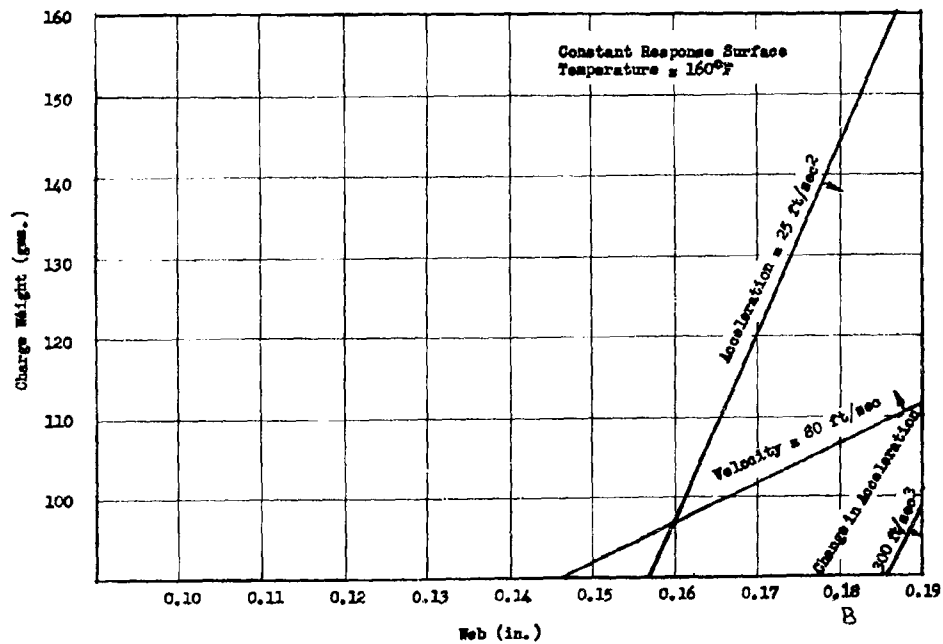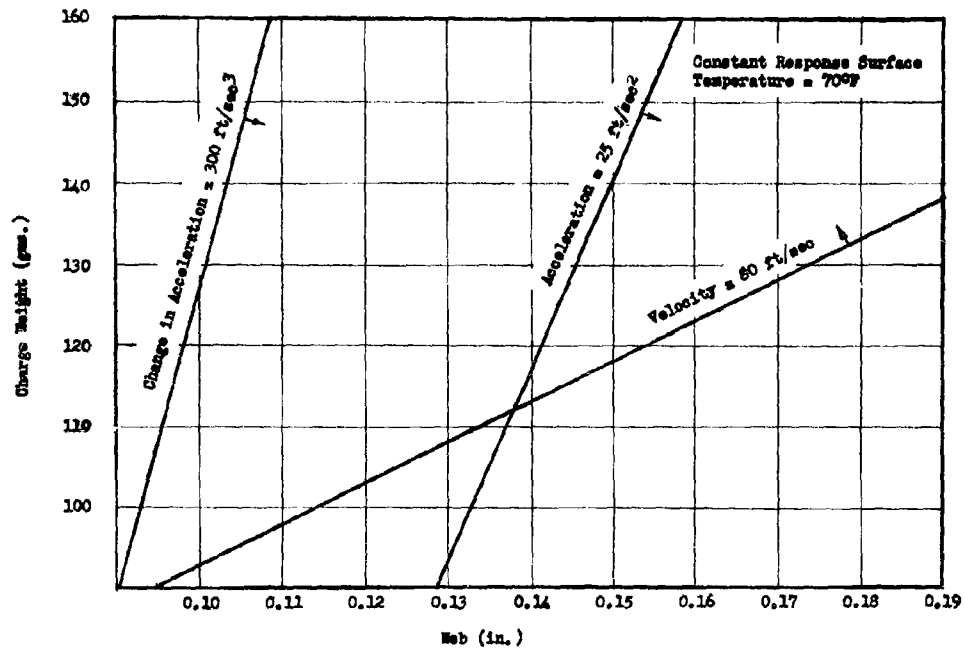A - Web = 0.16 in.
B - Web = 0.14 in.

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Figure 3.   Constant Response Surface
A – Temperature = 70° F
B – Temperature = 160° F

The next step was to form the six constant planes into a box. The response surfaces within the cube were obtained by joining the corresponding curves for g, $\overset{\bullet}{g}$, and v. Photo 1 (Appendix) shows this box. The thickness of the response surfaces is a result of round to round variation in ballistic performance. This illustration is qualitative; actual thickness must be determined from analysis of variance of the data.

An operating point (W_0, C_0, T_0) which satisfies performance requirements for this model must be within the cube volume defined by the three response surfaces. It is seen that the g and $\overset{\bullet}{g}$ requirements* are not met by all points within this space, with the exception of points in front of these planes (in the direction of the arrows). For example, the coordinates of point $W_0 = 0.158$ in., $C_0 = 121$ gm, and $T_0 = 85°$ F, give a web, charge, and temperature at which acceleration change is less than 300 g/sec, with a velocity greater than 80 fps. We see further that there is a volume surrounding this point over which the specifications will be met. We will call this volume the zone of suitable response. It has limiting values determined by the geometry of the response surfaces.

A better operating point might be found by extending the v, g, and $\overset{\bullet}{g}$ response surfaces outside the limits of the box. For example, it appears that a new constant web plane for webs greater than $W = 0.16$ inch will increase the temperature range over which desired performance is achieved.

In addition, the response surfaces may be extended in the direction of increasing or decreasing charge or temperature; thus, a volume space can be obtained over any desired range of web, charge, and temperature on the basis of a relatively few firings. (Other values, such as internal volume, expansion ratio, etc., could be used instead of those chosen for this particular model.) Any extension of the response surfaces outside the cube which represents experimental values is only as valid as the assumption that the response surfaces are planes. It becomes important, then, to learn something about the response surface. In particular, the hazards involved in interpolation and extrapolation should be studied. A start was made in this direction with a theoretical study of a thruster.

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*g $\leq$ 25 ft/second^2 and $\overset{\bullet}{g}$ $\leq$ 300 g/second

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THEORETICAL STUDY OF A THRUSTER

An analog computer was used to develop theoretical response surfaces for a thruster which moves a 500-lb load vertically.* Two restrictions were imposed:

1. Maximum pressure was to be less than 7000 psi;

2. Final velocity was to be greater than 7.5 fps.

About 60 computer runs were made for various design parameter combinations. The ballistic design parameters which were considered were: charge (C), propellant web (W), and chamber volume (V_c). The intersection lines of the response surfaces with the planes were obtained graphically from the results of the 60 simulations.

Figure 4A illustrates the intersection of the response surfaces with the plane $C = 3$ grams, while Figure 4B is the intersection with the plane $V_c = 1.3$ in.^{3} and Figure 4C, the intersection with the plane $W = 0.11$ in.

The three dimensional representation of the two response surfaces (pressure = 7000 psi and velocity = 7.5 fps) are shown in Photo 2 (Appendix). Some warping of the response surfaces can be seen. This illustrates a nonlinear response. However, the nonlinearity is well behaved. No oscillations, peaks, or humps occur. A linear interpolation should, therefore, be adequate if the box is small enough. At most, second order terms would be necessary. The size of the box should be small compared to nonlinearities, but large compared to nonuniformities.

Preliminary experimental work in ballistic development should be directed toward determining linearity and uniformity. This information is essential before setting up the factorial experiment so that the differences in performance levels will be significant and so that the complexities of nonlinear interpolation of the data can be avoided. In addition, this information should give some idea of the range of validity of extrapolations. However, it is a good practice always to verify extrapolation experimentally. (Proper preliminary work should eliminate the need for extrapolation.)

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*Details of computer simulation of ballistic devices can be found in the
following references:
   Frankford Arsenal Report R-1313, "An Analog Computer Study of
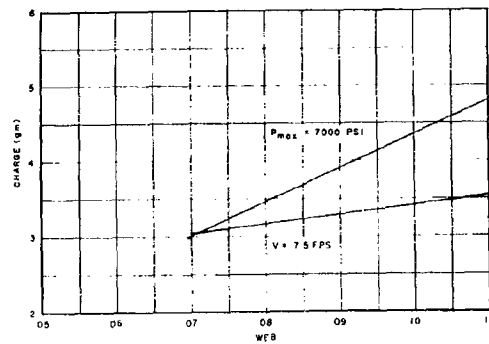Interior Ballistics Equations," March 1956, by L. Stout and W. A.
Dittrich
   Frankford Arsenal Report M61-17-1, "Analog Computer Study of
Interior Ballistics of Propellant Actuated Devices," April 1960, by
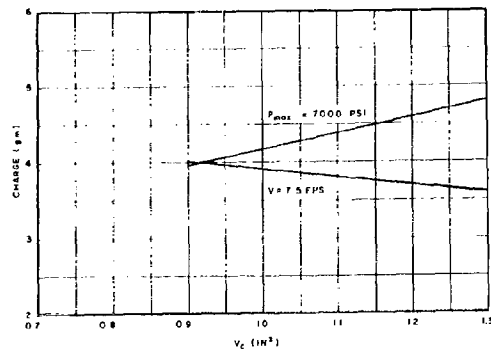R. Boritz and L. Narisi

A

B
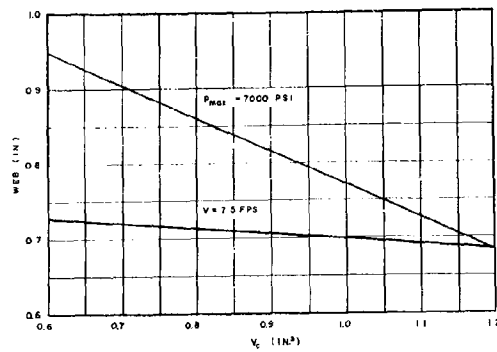
C

Figure 4. Intersection of the Response Surface with the Plane
A - Charge = 3 grams
B - Chamber volume = 1.3 in.^{3}
C - Web = 0.11 inch

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The operating volume of zone of suitable response is seen to be triangular in cross section, opening up in the direction of increased chamber volume and corresponding increased web. Thus, for an increased chamber volume, the range of web and charge over which the two restrictions would be met is greater. Picking a set of values for C, W, and V_c approximately in the center of the zone of suitable performance would thus minimize the chance of violating our restrictions because of performance variations that result from manufacturing tolerances. A larger chamber volume would allow substantial reduction of these tolerances. The actual chamber volume allowable, of course, is subject to the physical size of the thruster and other ballistic considerations, such as ignition and expansion ratio.

REACTIONLESS LAUNCHER STUDY

The reactionless launcher is a Davis type recoilless gun for ejecting masses from a ballistic missile during flight. The launcher holds two projectiles, as shown in Figure 5. In the particular project to be discussed here, the masses were intended to decoy anti-missile missiles.

The decoys are of many sizes and weights, and are launched at a wide range of velocities. The weight range considered was 20 to 60 pounds, and the velocity ranged from 50 to 110 fps. The wide range of performance required two types of interior ballistic systems, direct and high-low (shown in Figure 6). There are two types of projectile; the bullet type (full caliber), which fits directly in the bore of the gun, and the spigot type, which has a rod that fits in the gun barrel, with the payload outside the gun. These are shown in Figure 7.

The entire study involved a total of eight variables: ballistic system geometry, decoy geometry, charge weight, decoy weight, shot-start static breaking pressure, expansion ratio, propellant web, and orifice area (high-low system).

To blindly set up a factorial experiment at two levels would require the firing of 2^8, or 256, rounds. Replicating three times, which is reasonable for this type of study, would lead to firing more than 750 (of the order 10^3) rounds. Instead, we isolated factors with no interactions, such as the type of chamber - the high-low chamber was studied separately from the direct chamber. We divorced the spigot projectile from the bullet type for the direct system, but not for the high-low system since the high-low performance would not be expected to depend strongly on the type of projectile. As a result of this disjoining process, the study was split into three programs: A, B, and C.

In program A, a high-low chamber was used with a bullet type projectile. The main variables were: charge weight, shot-start static breaking pressure, * and orifice area of the high pressure chamber.

In program B, a direct chamber was used with a bullet type projectile. The main variables were: charge weight, propellant web, and shot-start static breaking pressure.

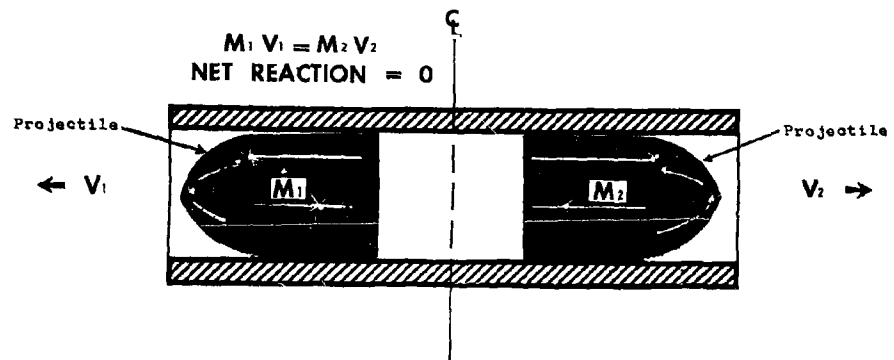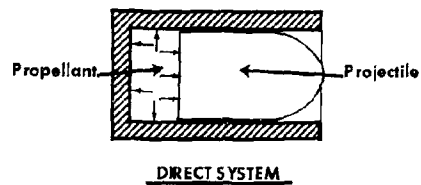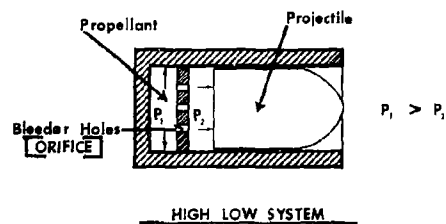*Shot-start is a rod which restrains projectile motion until chamber pressure reached a predetermined level.

$$M_1 V_1 = M_2 V_2$$
$$\text{NET REACTION} = 0$$

Figure 5. Reactionless Launcher

36.231.S0824/ORD.60

Figure 6. Interior Ballistic Systems, High-Low and Direct

a. FULL CALIBER

Projectile

Bore
Diam

b. SPIGOT
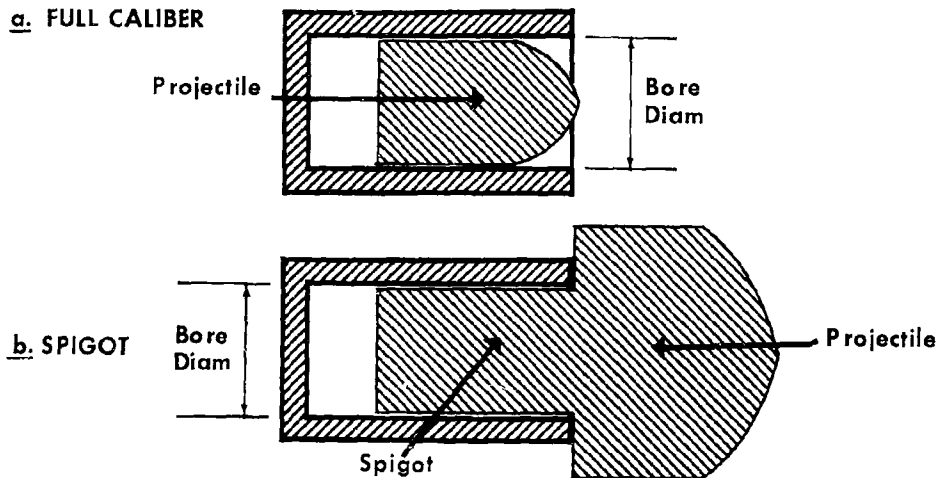Bore
Diam

Projectile

Spigot

Figure 7. Launchers, Full Caliber and Spigot Type

In program C, a direct chamber and spigot projectile were used. The main variables were: decoy weight, shot-start static breaking pressure, and spigot design (i.e., expansion ratio).

We fired factorial experiments at two levels for these variables (eight rounds for each program). For the three programs (A, B, and C), which were replicated three times, we fired a total of 8 x 3 x 3, or 72 rounds, a reduction by a factor of 10 in the number of rounds required. The change in the magnitude of t in the "Student t Test" is less than 5 percent for this change in the number of degrees of freedom and for confidence levels as high as 99.95 percent.

The discussion is being confined to the C program, as this amply illustrates the important points and the other programs are similar.

The statistical method used is found in Kempthorne.* The data taken were peak chamber pressures, peak acceleration, and the muzzle velocities of the projectiles. In addition, several other ballistic parameters (such as piezometric efficiency and ballistic efficiency) were examined. Each result was treated separately, in the manner

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*Kempthorne, Design and Analysis of Experiments, New York: John Wiley & Sons, Inc., 1952

outlined in Kempthorne, to obtain the effects of each variable and the interactions between variables. The significance of these values was ascertained by the use of the standard error and "t" test at both the 5 and 1 percent levels.

The values of the variables investigated in this program are shown in Table I; test results obtained are shown in Table II. Results of the factorial analysis are presented in Tables III, IV, and V, showing the effects and interactions of the variables on peak pressure, peak acceleration, and muzzle velocity, respectively.

In Tables III, IV, and V, a capital letter is used to represent the average effect of the corresponding parameters. In Table III, for example, $P = -2490$ psi represents the difference between the average peak pressure of all rounds fired with a closed spigot (closed spigot indicates large expansion ratio; consequently, this was considered the upper level of this parameter) and all rounds fired with an open spigot. Two capital letters written together ($W_t P$, for example) represent the interactions of the two corresponding parameters. Using data from Table III, $W_t P = -995$ psi; i.e., $\dfrac{500 - 2490}{2}$. Interpretation of effects and interactions follows.

The interpretation of effects and interactions is as follows. The main effect (P, for example) is the effect on the variable (pressure, in Table III; acceleration, in Table IV; and velocity, in Table V) of increasing expansion ratio (changing from closed spigot to open spigot) averaged over all possible combinations of projectile weight and shot-start values. It is desirable now to determine the effect of expansion ratio averaged over all shot-start values, but at the low projectile weight. This is denoted symbolically by $P - PW_t$.

In Table III, for example, $P - PW_t = -2180$ psi indicates that using data for 20-lb projectile weight only and averaging over all shot-start values, the peak pressure is reduced 2180 psi in changing from large expansion ratio (closed spigot) to small expansion ratio (open spigot). For data from the 60-lb projectile weight and all shot-start values (symbolically, $P + PW_t$), we have -2790 psi. The fact that $P - PW_t$ differs from $P + PW_t$ indicates an interaction between projectile weight and expansion ratio.

The results in Table III show that $W_t + W_t P = 200$ psi and $W_t - W_t P = 810$ psi. Therefore, the projectile weight effect when the open spigot is used is 200 psi; when used with the closed spigot, the projectile weight effect is 810 psi. The difference value of 610 psi (2790 psi - 2180 psi and 810 psi - 200 psi) is the interaction effect between expansion ratio and projectile weight.

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Table I. Variables Used in "C" Program

Constants: Propellant – MRSP (9201)
Web – 0.016 in.
Bore Dia – 2.25 in.

Variables	I		II		III		IV		V		VI	
Round number	1	2	3	4	5	6	13	14	15	16	17	18
Design shot-start breaking pressure, P_{ss} (psi)	none	800	800	none	none	none	800	800	none	800	800	800
Spigot	open	open	open	closed	open	closed	closed	open	closed	open	closed	open
Projectile weight, W_t (lb)	60	20	20	20	20	60	20	60	60	60	60	20
Round number	7	8	9	10	11	12	19	20	21	22	23	24
Design shot-start breaking pressure, P_{ss} (psi)	800	none	800	none	800	800	none	none	800	none	none	none
Spigot	closed	closed	closed	open	open	closed	closed	open	closed	open	closed	open
Projectile weight, W_t (lb)	60	20	60	60	60	20	60	20	20	20	20	60

Table II. "C" Program Test Results

Results	I		II		III		IV		V		VI	
Round number	1	2	3	4	5	6	13	14	15	16	17	18
Peak pressure (psi)	1630	1510	1500	3450	1380	4350	3800	1710	4350	1740	4550	1500
Peak acceleration (g)	108	316	314	686	289	288	755	113	288	115	301	314
Final velocity (fps)	72.5	130.4	131.2	163.3	133.5	93.8	164.5	70.9	93.8	71.8	93.0	130.4
Recoil impulse (lb-sec)	0.28	0.22	0.24	0.06	0.20	0.31	0.24	0.57	0.15	1.45	0.10	0.21
Round number	7	8	9	10	11	12	19	20	21	22	23	24
Peak pressure (psi)	4600	3500	4480	1630	1740	3800	4350	1400	3750	1440	3500	1470
Peak acceleration (g)	305	696	297	108	115	755	288	293	746	301	696	98
Final velocity (fps)	93.0	164.5	94.5	72.3	70.9	166.8	92.3	131.2	166.8	131.9	164.5	65.6
Recoil impulse (lb-sec)	0.07	0.12	0.15	0.24	0.61	0.10	0.13	0.19	0.46	0.10	0.35	0.13

Velocity for C-24 was obtained from P-T curve, using a planimeter.

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Table III. Effects and Interactions of the Variables on the Mean Peak Pressure, "C" Program*

Parameter	Average Effects	Spigot		Projectile Wt		Shot-Start	
		Open	Closed	60 lb	20 lb	800 psi	none
Spigot (P)	>2490			$P + PW_t$ -2790	$P - PW_t$ -2180	$P + P_{ss}P$ -2550	$P - P_{ss}P$ -2425
Projectile weight (W_t)	500	$W_t + W_tP$ 200	$W_t - W_tP$ 810			$W_t + W_tP_{ss}$ 490	$W_t - W_tP_{ss}$ 520
Shot-start (P_{ss})	190	$P_{ss} + P_{ss}P$ 125	$P_{ss} - P_{ss}P$ 250	$P_{ss} + P_{ss}W_t$ 170	$P_{ss} - P_{ss}W_t$ 200		
Standard error	18						

Mean peak pressure = 2800 psi
5% significant level = 39 psi
1% significant level = 55 psi

*All values expressed in psi

Table IV. Effects and Interactions of the Variables on the Mean Peak Acceleration, "C" Program*

Parameter	Average Effects	Spigot		Projectile Wt		Shot-Start	
		Open	Closed	60 lb	20 lb	800 psi	none
Spigot (P)	-300			$P + PW_t$ -185	$P - PW_t$ -420	$P + P_{ss}P$ -310	$P - P_{ss}P$ -290
Projectile weight (W_t)	-310	$W_t + W_tP$ -195	$W_t - W_tP$ -430			$W_t + W_tP_{ss}$ -325	$W_t - W_tP_{ss}$ -300
Shot-start (P_{ss})	-25	$P_{ss} + P_{ss}P$ 16.5	$P_{ss} - P_{ss}P$ 33.5	$P_{ss} + P_{ss}W_t$ 11.3	$P_{ss} - P_{ss}W_t$ 38.7		
Standard error	2.5						

Mean peak acceleration = 360 g
5% significant level = 5.4 g
1% significant level = 7.5 g

*All values expressed in g's

Table V. Effects and Interactions of the Variables on the Mean Muzzle Velocity, "C" Program*

Parameter	Average Effects	Spigot		Projectile Wt		Shot-Start	
		Open	Closed	60 lb	20 lb	800 psi	none
Spigot (P)	-26			$P + PW_t$ -22	$P - PW_t$ 30	$P + P_{ss}P$ -27	$P - P_{ss}P$
Projectile weight (W_t)	-62	$W_t + W_tP$ -58	$W_t + W_tP$ -65			$W_t P_{ss}$ -62.5	$W_t - W_t^2P_{ss}$ -6
Shot-start (P_{ss})	-0.06	$P_{ss} + P_{ss}P$ -0.83	$P_{ss} - P_{ss}P$ 0.95	$P_{ss} + P_{ss}W_t$ -0.08	$P_{ss} - P_{ss}W_t$ 0.20		
Standard error	1.1						

Mean muzzle velocity = 108 fps
5% significant level = 2.4 fps
1% significant level = 3.4 fps

*All values expressed in fps

For a pictorial representation of the results, the variables are laid out as the axis of a transparent cube. The corners of the cube represent the eight combinations of variables fired. The yields (velocity, acceleration, and peak chamber pressure) are assumed to vary along the edges of the cube according to the predictions of ballistic theory. Thus, the yields at the corners are interpolated to obtain planes of constant response. (Ideally, an analog computer analysis is desirable to calculate the planes exactly, as was done for the thruster previously discussed.)

The planes indicated in Photo 3 (Appendix) represent: peak pressure, 2800 psi; velocity, 108 fps; and peak acceleration, 360 g's. Points within the transparent cube above the red surface (designated P) represent variables which result in pressures below 2800 psi. Similarly, points in front of the V surface (green) are below 108 fps, and behind the G surface are less than 360 g's. Thus, the three surfaces enclose a polygon of triangular cross section which is the zone of suitable response.

Combinations of variables near the surface of the zone may result in unsuitable performance as a result of round-to-round variations. Analysis of variance from the results of the factorial analysis and interpolation of the variance along the cube edge, using the same technique as in interpolating the yields, allows us to ascribe a thickness to the response surface. To illustrate this, the zone of suitable performance has been removed from the cube in Photo 4 (Appendix). The zone of suitable performance now appears as three boards nailed together. The hollow space is known as the zone of acceptable variables.

Performance confidence requirements, reliability requirements, and the experimental data determine the thickness of the surfaces. Only one way of applying this method is illustrated. The response surface of finite thickness would be used to construct the zones in different ways for different performance requirements. Suppose the velocity were required to be 108 ± 5 fps instead of simply greater than 108 fps, still keeping the pressure and acceleration requirements as before. Then the zone of suitable response would be represented by the green board marked V in Photo 4. The zone of acceptable variables would be represented by a surface running along the board, bisecting the thickness. There is an extremely wide variety of requirements that can be treated with this technique. No unusual or exotic statistical mathematics is required.

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CONCLUSIONS AND RECOMMENDATIONS

Our general conclusion is that the use of factorial type experimental design programs represents a definite advantage to the ballistic designer. These advantages are measured in terms of a larger number of variables investigated for fewer rounds (time and money economy). In addition, interaction effects among the variables are determined. Adding the Box technique and pictorial representation to the use of factorial experiments in ballistic research gives the experimenter a more economical and vivid picture of how the variables operate. To this picture may be added the variances of each response. Thus, a zone of suitable performance may be determined in which the greatest reliability of operation is obtained.

In the design of ballistic devices it is recommended that factorial experiments be conducted and combined with a "box" representation of the results.

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RESPONSE SURFACES
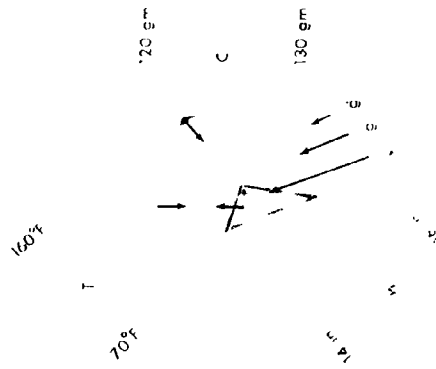
THRUSTER

Photo II

REACTIONLESS LAUNCHER

Photo IV

M-5 AIRCRAFT SEAT EJECTION CATAPULT

Photo I

REACTIONLESS LAUNCHER

Photo III

19
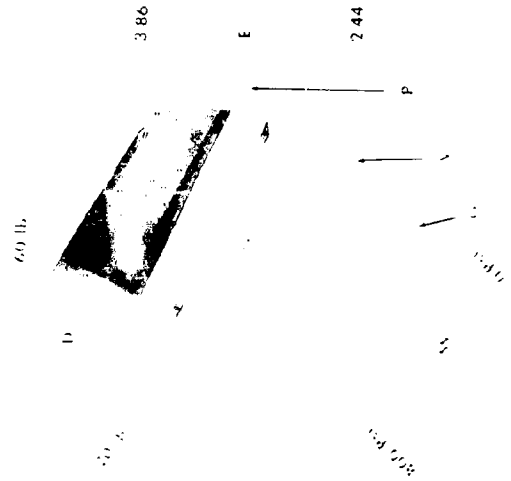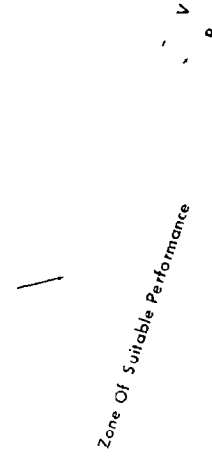
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APPLICATION OF FACTORIAL EXPERIMENT AND BOX
TECHNIQUE TO BALLISTIC DEVICES By D. J. Katsanis
and C. L. Fulton   UNCLASSIFIED REPORT

Report R-1592, June 1961; 22 pp incl illus and tables
DA Project 502-06-001 OCO Project TS1-15

In an effort to reduce the time and cost of ballistic
experimental development projects, the factorial experi-
ment and Box technique have been applied to ballistic
experiments with aircraft seat ejection catapults and
rockets, high-low guns, Davis guns, and recoilless rifles.
This has resulted in a reduction in the number of rounds
fired, with little or no reduction in the validity of the
analysis of variance.
A detailed discussion of application of the Box tech-
nique to the factorial data is presented. This application
results in the determination of a "zone of suitable per-
formance" which makes use of interaction effects to pro-
vide greater flexibility in the selection of design para-
meters.

ACCESSION NO.

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1. Box Technique
2. Factorial Experiment Design
3. Statistics
4. Ballistics
5. Propellant Actuated Devices

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